SOFT TISSUE RECONSTRUCTION FOR CRANIOFACIAL SURGERY PLANNING

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ABSTRACT

Computer Assisted Surgery (CAS) systems strive to enhance the surgeon's capabilities to utilize medical imagery to decrease the invasiveness of surgical procedures and increase their accuracy and safety. Image guided surgery systems facilitate surgical planning and analysis by aligning various datasets with information on morphology (MR, CT, MR angiographies), cortical function (fMRI) or metabolic activity (PET, SPECT). These systems are categorized into performing one or more of the functions such as data analysis, surgical planning and surgical guidance, etc. The surgical planning systems present surgeons with data gathered prior to surgery and facilitate in plotting an approach trajectory that avoids critical structures such as blood vessels etc. Computer tomography (CT) and magnetic resonance imagery (MRI) has had an enormous impact in medicine during the past two decades and has been widely used for surgical planners. Craniofacial anomalies and fine anatomic details of facial traumic injuries can be well studied with such imaging techniques. The research focuses on development of a system for simulation of craniofacial reconstruction surgery that is based on volumetric object models derived from 3D Computer Tomography (CT) imaging. Feedback is provided to the user via real-time volume rendering. The system is the result of collaboration between a university, an industrial research organization and a research hospital. In this paper, components of the system are detailed and the current state of the integrated system is presented. Issues related to future research and plans for expanding the current system are discussed.

Keywords: CAS, CT, MRI, Surgery Planning.

1.0 Introduction

Complex maxillofacial malformations continue to present challenges in analysis and correction beyond modern technology. Current surgical procedures attempt to re-establish functional and aesthetic anatomy by repositioning displaced skeletal elements or by grafting and contouring abnormal bony contours. Principally, soft tissue changes are the results of these skeletal alterations.

Surgical planning is determined by quantitative analysis, clinical and aesthetic judgment. Computer-generated three-dimensional imaging of maxillofacial anatomy, obtained from spatially mapped data by computed tomography (CT) and magnetic resonance imaging (MRI) techniques can provide the accurate life size and shape of an object such as the skull. Three-dimensional (3D) visualization is the essence and aim of three-dimensional imaging systems.

In the next section, we present the related work done in the this area. Section 3 presents “Computer System”, “Computed Tomography (CT) Scan”, “3D Laser Scan of the Head”, “Soft Tissue Reconstruction of CT data” and “Visualization Pipeline”. Results have been presented in section 4. Finally, section 5 presents the discussion.

2.0 Previous Work

The field of facial modeling has been an area of growing research efforts for more than a decade. First approaches were based on geometric deformations using parametric surfaces and aimed primarily at facial animation. Later, physically based simulation paradigms were adopted in order to model more accurately the physical properties of elastic materials [1].

First concepts of 3-D planning in craniomaxillofacial surgery, including soft tissue prediction, can be found in Cutting *et al*. [2]. Active research started approximately 16 years ago. Larrabee [3] stated a finite element model of skin deformation. This work was followed by Deng’s PhD thesis [4], where she presented an analysis of plastic surgery by means of the finite element method. In 1991, Pieper [5] summed up his efforts to provide a system for computer-aided plastic surgery in his PhD thesis. He focused on plastic surgery and therefore concentrated on cutting and stretching of skin and epidermis rather than on repositioning bones. Further, his model lacked the resolution [1] required for a reliable simulation of very subtle changes in the appearance of a face and did not provide a C1-continuous surface.

Lee et al. [6] presented a promising approach to facial animation where they introduced a layered tissue model based on masses and springs connected to form prism-shaped elements. The facial model is adapted from a template face, takes into account various anatomical aspects and aims at facial animation. Koch et al. [7] proposed a method, which provides a C1-continuous finite element surface connected to the skull by springs. This model is generated directly from individual facial data sets and has successfully been tested for surgery simulation and emotion editing [7] on the Visible Human Data Set. Although providing very promising results the model lacks true volumetric physics.

Girod *et al*. [8] present s system for surgery planning based on CT data. The 3D geometry of the head and the color of the skin surface are measured using a 3D laser scanner. For simulating craniofacial surgery, the bony skull is acquired by segmentation of CT data into "air", "tissue" and “bone”. For the visualization of volume data, surface based methods are used. The "Marching Cubes" method uses only surface information of the object for visualization. Dissection of bone has been simulated using a "cutting plane".

Roth [9] presented a versatile framework for the finite element simulation of soft tissue using tetrahedral Bernstein-Bézier elements. They incorporated higher order interpolation as well as incompressible and nonlinear material behavior, but again restricted themselves to C^0-continuous interpolation across element boundaries. Koch *et al*. [1] simulated surgical procedures such as the bone cuts (osteotomies) and bone movements (e.g. advancement of the jaw bone) with the help of a craniofacial surgeon using the Alias™ modeling system. To optimize both accuracy and rendering quality, Koch *et al*. [1] combined the physical correctness of volumetric finite element simulation with the superior quality of the C^1-continuous surface.

Troulis *et al.* [10] developed a system for three-dimensional visualization of the facial skeleton, selection of landmarks, measurement of angles and distances, simulation of osteotomies, repositioning of bones, collisions detection and super-imposition of scans. For the surface-model generation, "3D Slicer" [11], a visualization software for medical images, was used to semi-automatically segment the bone. This software was developed by Gering *et al*. [11], at the Surgical Planning Laboratory (SPL, Brigham and Women's Hospital, Boston, MA, USA) and is an 'open-source' application available on the internet (http://www.slicer.com). Once the segmentation is obtained, the 3D Slicer generates triangulated surface models of the skeleton and skin using the marching cubes method [12] and triangular surface decimation [13].

3.0 Materials and Method

3.1 Computer System

An IBM-compatible Personal Computer (PC), configured as an Intel® Pentium-IV® 2.8 GHz processor (Intel Inc., CA, USA) with 1.00 GB RAM, an ATI RADEON display card with 256 MB RAM. The operating system was Microsoft® Windows XP 2002, Home Edition, Service pack 2. All the programs were developed by Microsoft® Visual C++ 6.0 and Visualization Toolkit (VTK).

3.2 Computed Tomography (CT) Scan

For patients with complex craniofacial deformities, a preoperative CT scan is performed at Hospital University Science Malaysia (HUSM), Kota Bahru, Malaysia. The family of CT scanners used is GE CT scanner, which acquires cross sectional 512x512 images (Fig. 3.1).

The form of output from these scanners is Digital Imaging and Communication in Medicine (DICOM). To scan a complete head, the output consists of 204 slices, slice thickness is 1.25mm and data resolution is 12 bit. The DICOM file contains both a header (which stores information about the patients name, the type of scan, image dimension, etc), and the image data (which contains information in two dimension (one slice) or three dimensions (a collection of slices forming a volume) [14].

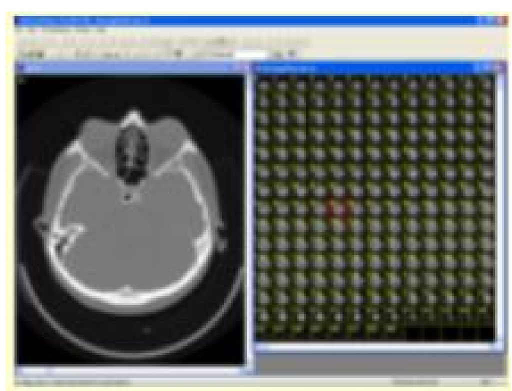

Figure 3.1. CT-Slice images

3.3 3D Laser Scan of the Head

The 3D geometry of the head and the color of the skin surface are measured using 3D laser scanners. The family of three-dimensional non-contact laser scanners used is Minolta VIVID 910. Since it takes approximately 03 sec to complete the procedure, it is possible to scan living objects. In this research two Minolta VIVID 910 laser-scanning systems have been used. Once the data are collected the object can be visualized from different angles on a graphics workstation using the geometry and reflection data. This 3D laser scan data is used for the photorealistic simulation of the postoperative appearance of a patient. Further details can be found in [15]. Figure 3.2 shows a registered image of 3D laser scanner.

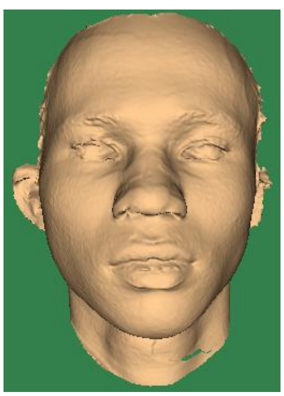
Figure 3.2. 3D Laser scan of a patient

3.4 Soft Tissue Reconstruction of CT data

The collection of all points in a volume with a given scalar value is called a level surface, also known as iso-surface. The scalar value that defines the iso-surface is called the level of the surface. A surface is generally constructed using polygons as primitives. Standard computer graphics techniques, such as shading models (like Phong or Gouraud shading), can be applied to the polygon meshes and then the meshes can be rendered efficiently with the use of optimized hardware.

The overall distribution of a three-dimensional scalar field ρ(x) can be indicated by constructing a c-isosurface

$$S = \{x \mid \rho(x) = c\} \qquad (3.1)$$

which consists of all points x where the field value ρ(x) equals a given isovalue c. The surface divides the domain into regions where the scalar field is either greater or smaller than the isovalue c.

One of the most popular algorithms for iso-surface generation is the marching cubes [16] algorithm. In a three-dimensional scalar field, cells are defined as rectangular sub-regions with eight vertices. The algorithm assumes a linear variation in each direction within the cell. The idea is to march through the domain cell by cell and determine whether the surface passes through the cell. If it does, we need to determine the polygons that make up the surface. According to the set of vertices of the cell that are inside or outside the surface, a look-up table with the possible combinations of how the surface passes through the cell is used to determine the polygons to be used.

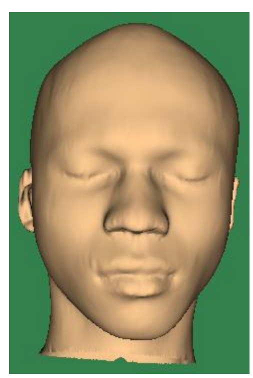
Figure 3.3. Soft tissue reconstructed from CT data

The "3D-Slicer" [16], a visualization software for medical images, is used to semi-automatically segment the bone and soft tissue. This software was developed by Gering *et al*. [17] at the Surgical Planning Laboratory (SPL, Brigham and Women's Hospital, Boston, MA, USA) and is an 'open-source' application available on the internet [16]. Once the segmentation is obtained, the 3D-Slicer generates triangulated surface models of the skeleton and skin (Figure 3.3) using the marching cubes method [12] and triangular surface decimation [13]. The threshold values for segmentation of hard and sot tissues by using 3D-Slicer are listed in table 3.1.

Table 3.1. Threshold for tissue segmentation

Tissue Type	Threshold Value
Soft Tissue	884
Hard tissue	1284

3.5 Visualization Pipeline

The Visualization Toolkit (VTK) [18] has been designed to facilitate scientific visualization in general and can be used in medical applications. Unlike commercial products, VTK is a free, open-source project supported and extended by the contributions of a community of developers. It provides a wide variety of algorithms for visualization and image processing, and follows a data-flow model, where module inputs and outputs can be interconnected to create a visualization pipeline. In general, a pipeline consists of objects to represent data, objects to operate on data and a direction of data flow [19]. Figure 3.4 shows visualization pipeline for the system.

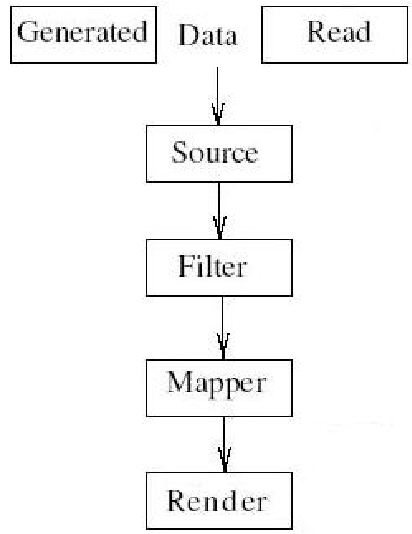

Figure 4.1. VTK visualization pipeline

4.0 Results

The focus of this research is to develop a surgical planner that can be applied for diagnostic visualization, and planning surgical procedures and planning approach trajectory in craniofacial reconstruction surgery. Prior to surgery, pre-operative data sets (CT data and Laser Scanner data) are fused with a robust registration process. Then this merged data is visualized in an interactive 3-D graphics environment.

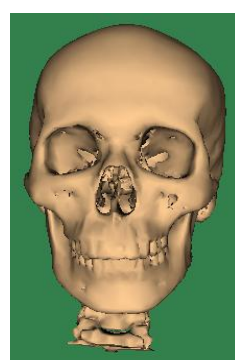

Figure 4.1. Hard tissue reconstructed from CT data

Figure 4.1 displays hard tissue reconstructed from CT scan data of a patient. The soft tissue data of the same patient was measured using 3D laser scanner. Figure 4.2 shows the laser scan soft tissue superimposed on hard tissue of the patient.

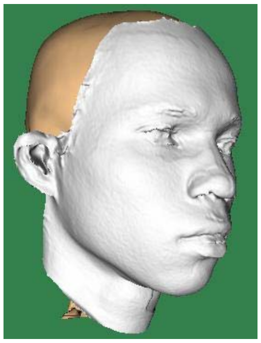

Figure 4.2. Soft tissue (laser scan) superimposed of hard tissue (CT data)

Figure 4.3 displays soft tissue reconstructed from CT scan data superimposed on laser scan soft tissue. The difference in the two surfaces is shown in figure 4.4 as distance color plot. Average difference in distance of the two surfaces is 0.99582mm and standard deviation is 1.13229. The average difference of less than 1mm is within the acceptable range for medical applications.

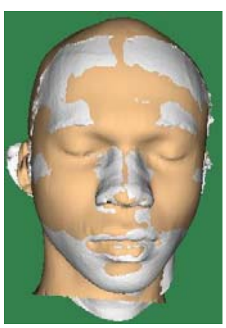

Figure 4.3. Soft tissue extracted from laser scan (white color) superimposed on soft tissue reconstructed from CT data (off-white)

A large surface distance of 6.23041 has been observed in the eye's region. Where as in the cheeks regions, the difference is in the range of 1.5mm.

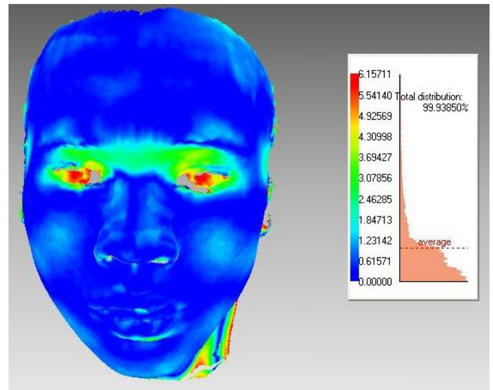

Figure 4.4. Color plot displaying surface difference of Soft tissue extracted from laser scan data and soft tissue reconstructed from CT data

5.0 Discussion

Medical imaging modalities used to get anatomical/structural information includes X-ray radiography, X-ray mammography, X-ray CT, ultrasound and MRI. X-ray radiography is the oldest medical imaging technique that is still one of the most widely used methods in diagnostic radiology because of its simplicity, portability and low cost. It is also being used for breast mammography and is very effective in detection of breast cancer at earlier stage. In case where 3D anatomical information is required, CT, ultrasound or MRI is the choice.

CT images have a very high spatial resolution and provide very good contrast between soft tissues. The major disadvantage of X-ray and CT imaging is the fact that these techniques use radiations that can cause tissue damage and there is a limit on the total radiation dose per year to which a patient can be exposed. MRI gives excellent soft tissue contrast and high spatial resolution. The scanning time is between 3 to 10 minutes and is much more susceptible to patient motion. The cost of MRI scanner is higher than others.

Anatomical imaging modalities are limited to the structural information and do not provide any functional or metabolic information about an organ or tissue in body. Medical imaging modalities used to get functional information include fMRI, SPECT and PET. SPECT imaging is rich of functional/metabolic information and is a prove tool in the characterization of tumor. However, SPECT images are poor in resolution and anatomical information as compared to CT or MR images. SPECT imaging is a low-cost imaging modality compared to PET because of the lower preparation cost of the radioisotopes used for imaging.

The CT scan provides good contrast for soft and hard tissue but it lacks the texture details, so it makes it difficult to select the landmark for analysis process and shape analysis is subjected to more errors.

On the other hand, 3D laser scan provides very quick methods for measurement of soft tissues. It takes few second to measure soft tissue, so is subjected to less movements of patient. Also it provides good texture contrast and as a result the selection of landmark point is easy and prone to less errors. This research has used both type of data for soft tissue. The surface distance for these two types of tissue is within acceptable limit.

A large surface distance of 6.23041 has been observed in the eye's region. The reason may be that the patient's eyes were closed in CT scan while in laser scan the eyes were open. Where as in the cheeks regions, the difference is in the range of 1.5mm. The reason may include that the laser scan was taken after almost one month of the CT scan, and during this time there were changes in the soft tissues of this region.

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